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Anaerobic fermentation technology increases biomass energy use efficiency in crop residue utilization and biogas production

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A B S T R A C T

A biomass energy utilization project (Corn stalk → Cattle → Cattle dung → Biogas digester → Biogas/ Digester residues → Soil) was conducted in a typical temperate agro-village of China from 2005 to 2010. The present study focused on two key approaches of the ecological loop: (1) increasing corn stalk use efficiency by improving anaerobic fermentation technology; and (2) enhancing biogas productivity by optimizing fermentation conditions. Our results showed that crude protein and fat of corn stalks significantly increased, while crude fiber content and pH decreased considerably during anaerobic fermentation. The cattle digestion rate, forage consumption and increases in cattle weight were higher in cattle fed fermented corn stalks than in those fed non-fermented corn stalks. The rate of biogas production was higher (78.4%) by using cattle dung as a substrate than using crop residues. Heat preservation measures effectively enhanced the biogas production rate (12.3%). In 2005, only two cattle were fed in this village, with only 1.1% corn stalk utilized as forage. No more than three biogas digesters existed, and the proportion of biogas energy used in total household fuel was only 1.7%. At the end of the 5-year experiment, the number of cattle capita reached 169 with 78.9% corn stalk used as forage. Biogas digesters increased to 130, and the proportion of biogas energy used in total household fuel was up to 42.3%. A significant positive correlation was noted between the increasing rate of farmers' incomes and the proportion of corn stalks used as forage. Available nutrients were higher in fermented cattle dung than in fresh cattle dung. Our findings clearly suggest that anaerobic fermentation technology is important in enhancing crop residue use efficiency, biogas productivity and soil fertility. Fermentation technology may help reduce the use of fossil fuels and improve the environment in rural areas.

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1. Introduction

Energy crisis and global warming are considered to be two most serious problems worldwide [1]. Biomass energy, as a renewable and sustainable form of energy, is becoming more important due to its environmentally-sound and energy-saving production methods [2]. Development of a livestock industry is believed to be a key approach to effectively consume redundant crop residues in agricultural areas by reducing energy waste and environmental pollution created by discarding or combusting residues in the field [3–5]. The energy use efficiency of crop residues has been limited by inadequate use of the forms of energy, such as carbohydrates and proteins [6,7]. Therefore, it is vital to determine how to increase the digestion rates of nutrients in crop residues in livestock forage.

Due to its lower capital investment and operating expenses, anaerobic fermentation is an economical process naturally realized by anaerobic bacteria that improves the nutrient availability of crop residues and enhances biogas production [8–10]. Biogas production and utilization represent dual goals of improving environmental conditions and sustainable energy production in rural areas [11]. Therefore, biogas utilization might be a promising strategy to reduce fossil energy consumption and greenhouse gas emission in developing countries, especially in China and India [1].

1.1. Crop residues production and utilization in rural China

Some 630 million tons of crop residues are produced each year in China, of which nearly 80% are corn, wheat and rice. Unfortunately, only 23% of the crop residue is used as forage, 0.5% is used as biogas, 37% is used as energy by farmers, 15% is lost during collection and 20.5% is discarded or directly burnt in the field [4]. By all accounts, a large amount of biomass is wasted or inefficiently used. The main reason crop residues are not used more as forage is because of its characteristic poor digestion rate [12–14]. Therefore, investigating methods to increase the digestion rate of crop residue is extremely important in reducing energy waste and environmental pollution in rural areas of China.

Here, we focus on the usage of corn stalk because it is the major crop residue utilized as livestock forage in agricultural areas of China. Conventionally, non-fermented corn stalks are used as forage with very low use efficiency [15–17]. Large parts of the corn stalks are discarded or directly burnt in the field, leading to serious environmental pollution and traffic accidents [18]. Although the Chinese government has issued some laws prohibiting burning crop residues in fields [19,20], this has achieved little because farmers are hard-pressed to find proper ways to consume the abundant crop residues.

1.2. Livestock feeding and anaerobic fermentation technology

In the past, livestock (cattle, sheep, etc.) feeding developed slowly in agricultural areas due to the high cost of buying animal feedstuffs. Non-fermented corn stalk is not favorable forage for cattle because its high fiber content and low digestibility [21,22]. As a result of the development of fermentation technology, more corn stalks are being used as cattle forage. The costs of feeding cattle are declining and farmers can obtain considerable profit from feeding cattle, which has led to the rapid development of feeding crop stalks to livestock in recent years [7,23]. The considerable development of the livestock industry in agricultural areas is also due to the inability of increasing livestock numbers in typical grasslands because of the serious degradation caused by continual overgrazing in those areas [24,25]. Thus, livestock feeding in agricultural areas is becoming more important in meeting current and future human requirements for meat and milk [26].

Nevertheless, traditional fermentation technologies for crop residues are fairly rudimentary in rural China. Typical fermentation methods involve farmers digging a large pit in a field, covering the crushed crop residues with plastic film and then airproofing and piling soil on top of the pit. After fermenting for 30 days, the crop residues are gradually taken out to feed the cattle. The limitation of this type of processing is that much of the crop residue in the pit rots before being fed to the cattle. This is caused by exposure to oxygen each time the plastic film is opened, which leads to a tremendous decrease in feed quality. Therefore, the fermentation technology of crop residues needs to be greatly improved.

1.3. Fermentation technology used in biogas production

In China, some 550 million household digesters and 2360 biogas stations had been installed by the end of 2007 [27]. Biogas production and utilization in rural areas have been highlighted by policy makers for almost three decades [4,28]. However, a full year's biogas output, especially for household digesters, is typically extremely low due to both improper substrate (crop residues are directly placed in biogas digesters) and low temperatures in late fall and winter [29,30]. Recently, cattle dung output has increased due to livestock development in agricultural areas of China. Cattle dung may contain more anaerobic bacteria than crop residues because it comes from the cattle's digestive system [12,18]. Therefore, in this study, we used cattle dung as the main digester substrate combined with heat preservation facilities installed around and above the digesters to elevate temperatures in biogas digesters. We hypothesized that those measures might significantly improve conditions of anaerobic fermentation and increase biogas productivity.

The objectives of the present study were to investigate (1) whether improved anaerobic fermentation technology could enhance crop residue nutrient contents and digestion rates of cattle; and (2) whether the combined use of cattle dung as the main substrate and the installed heat preservation facilities for the biogas digester could enhance biogas productivity and supply the majority of household fuel needs in rural China. This is the first and largest experiment carried out in China that includes

treatment of crop stalks, feeding cattle and biogas production. The findings from this study might help governments correctly guide the utilization of bio-resources in agricultural areas worldwide, especially in developing countries.

2. Materials and methods

2.1. Background of corn stalk and biogas utilization in the study area

This study was conducted in Jiangjiazhuang, a typical temperate agronomic village, located in southeastern Shandong Province, China. About 421.3 t of fresh corn stalks were produced each year between 2001 and 2010 (Fig. 1). Prior to our study, most corn stalks were stacked around farmers' houses or along the streets after harvest (Fig. 2). Conventionally, farmers in this village use parts of the stalks as household fuel and a small portion as cattle forage, while large amounts are wasted. After a period of being stacked in open air, the corn stalks turn yellow and dry, and as a consequence, become unpalatable to cattle. The farmers must buy expensive forage for the cattle, which results in reduced profits from feeding cattle, thereby resulting in low numbers of cattle. In 2005, only 2 cattle were fed in this manner, and the proportion of corn stalks used as cattle forage was about 1.1%.

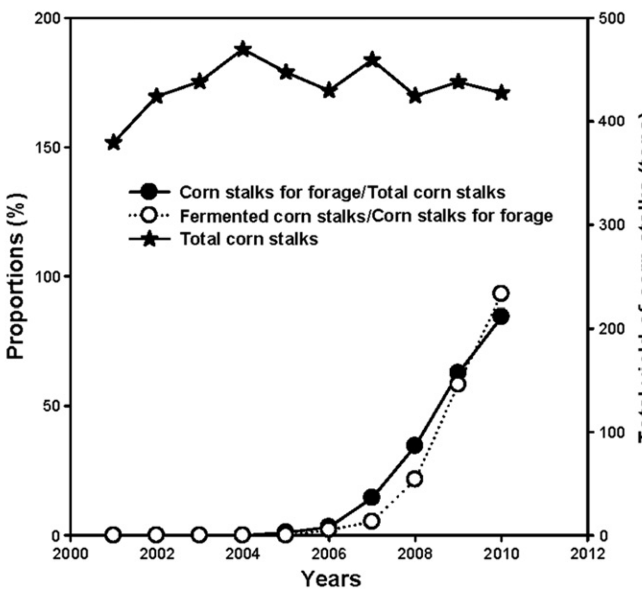

Fig. 1. Total yield of corn stalks, the proportions of corn stalks used as forage/total corn stalks and fermented corn stalks/corn stalks used as forage from 2001 to 2010.

Fig. 2. Before the experiment, crop residues (including corn stalks) were stacked in the streets.
Photo source: Jiang Gaoming.

Total energy consumption in Jiangjiazhuang increased gradually from 2001 to 2010 (Fig. 3). However, biogas digesters, biogas production and the proportion of biogas energy used in household fuel did not increase significantly before the start of the project. In the past, crop residues directly used as biogas substrate combined with low temperatures in late fall and winter substantially limited biogas productivity. As a consequence, the biogas output was too low to meet fuel requirements for farmers' households through the entire year. This has resulted in low dependence on biogas as a fuel source and little interest in developing biogas utilization in rural areas of China.

The integrated project was designed as an agricultural chain: corn stalks → fermented forage → cattle → cattle dung → biogas digester → biogas/digester residues → croplands. The present study focused on two key approaches in the above agricultural loop: (1) to elevate corn stalk nutrient content and cattle digestion rates by introducing and improving anaerobic fermentation technology; and (2) to enhance biogas productivity by optimizing digester substrate composition and elevating digester temperature.

2.2. Corn stalk anaerobic fermentation

The fresh corn stalk fermentation experiment utilized three treatments: micro-cake fermentation (''bread'' forage),

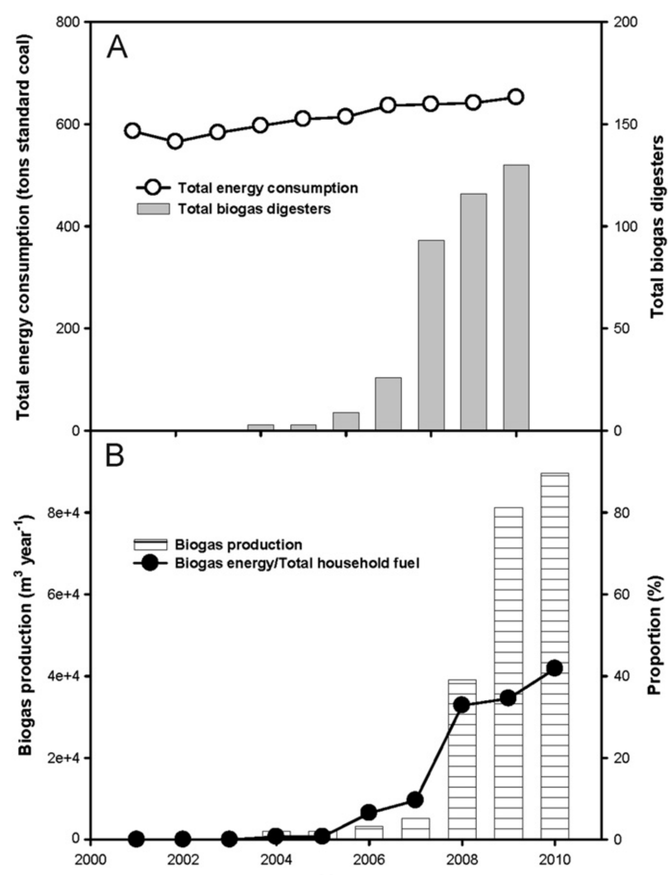

Fig. 3. Total energy consumption and biogas digesters (A), biogas production and the proportions of biogas energy in total household fuel consumption (B) from 2001 to 2010.

huge-fermenter fermentation (''huge-fermenter'' forage) and non-fermentation (traditionally stored corn stalks). The non-fermentation treatment was used as a control.

The ''bread'' forages were processed by the following method. Fresh corn stalks were immediately reaped after the ears were harvested at maturity. The crushed and kneaded corn stalks were pressed and framed in a cylinder shape measuring 52 cm in diameter and 52 cm in height (Fig. 4). The cylinders were then wrapped tightly within plastic film and stored in dark conditions for anaerobic fermentation (Fig. 5).

The huge fermenter measured $80 \times 10 \times 4\ m^3$ (length $\times$ width $\times$ height), which was divided into 20 small chambers with doors of adjacent chambers facing opposite directions (Fig. 6). This arrangement effectively reduced the amount of oxygen entering into the entire fermenter every time the door of each chamber was opened. The ''huge-fermenter'' forages were processed as follows. Fresh corn stalks were crushed into pieces by pulverizers and poured into each chamber in the huge fermenter. They were then pressed tightly and covered with plastic to create anaerobic conditions.

After 30 d of fermentation, the physical characteristics (smell, pH and water content) of ''bread'' forages and ''huge-fermenter'' forages were tested, and biochemical parameters (crude protein, crude fat, crude fiber content, etc.) of the fermented/non-fermented corn stalks were measured.

Fig. 4. The scene and the process of making ''bread'' forages by corn stalks.

Fig. 5. The shape of the completed ''bread'' forages.

Fig. 6. Huge operating fermenter for fresh corn stalk storage and fermentation.

2.3. Observations of cattle growth

Fifteen 200–220 kg calves were chosen to track the growth of the cattle. The cattle were randomly separated into three groups, and each group was fed forage of different treatments. For forage treatments, the standard feedstuff (consisting of corn powder, bran, bean cake, bone powder, salt, etc.) was the same, while the other portion of the forage included treated corn stalks (non-fermented corn stalks, ''huge-fermenter'' forage and ''bread'' forage). The cattle were fed twice a day with a certain amount of standard feedstuff and adjustable amount of differently-treated corn stalks. Drinking water was offered freely. Forage consumption and cattle weight were recorded 8 times at an interval of 1 month for the duration of the experiment.

2.4. Biogas production

Three household biogas digesters (measuring about $7\ m^3$) were built underground with adiabatic materials encircling and greenhouses covering the top to elevate temperatures in the biogas digesters (Fig. 7). Cattle dung was used as the main biogas substrate. The biogas substrates (cattle dung + human excreta + pachyrhizus bine + water) were filled in the biogas digester through the inlet in the toilet. The proportion of the substrate was 9:1, cattle dung:pachyrhizus bine. A biogas hydrometry meter (ZG-2, Kaitai Instrument Co. Ltd., Zhejiang, China) was installed beside each biogas digester. After 30 d of fermentation, the biogas productivity was recorded at 10-d intervals.

2.5. Chemical analysis

Corn stalk nutrients, water content and digestion rates of differently-fermented corn stalks were analyzed in the Laboratory of Shandong Agricultural University. Nitrogen content (N) was determined following the Kjeldahl Nitrogen Determination method [31]. Crude protein content (PC) was calculated by using the formula

$$PC(mg\ g^{-1}\ dm) = N \times 5.7$$

Crude fat and crude fiber contents were measured according to the method described by Zhao et al. [32]. To determine water content (WC), samples of differently-fermented corn stalks were weighed to obtain fresh mass (FM), then dried to consistent weight to record dry mass (DM). WC was calculated by using the formula

$$WC(\%) = (FM - DM)/FM.$$

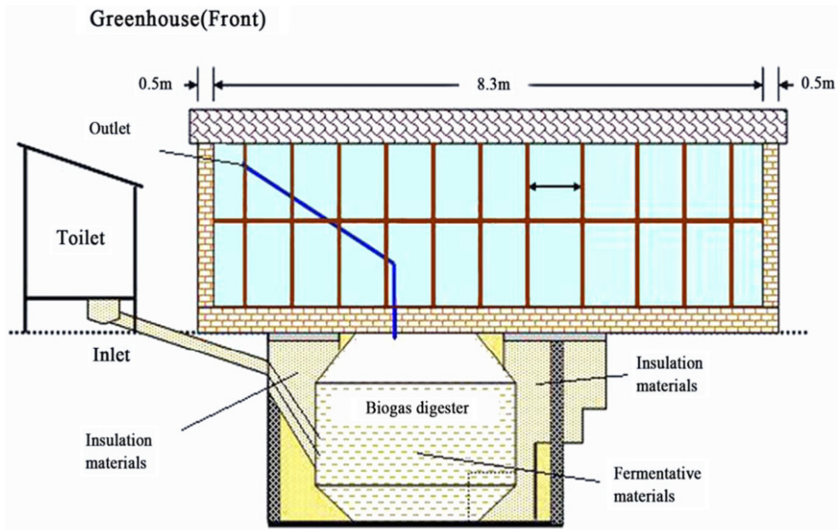

Fig. 7. Schematic of the biogas digester structure with heat preservation measures.

Table 1
Water content, pH, nutrient components and cattle digestion rate of 30-d fermented and non-fermented corn stalks. Data are means ± SE (n=3). WC stands for water content; DR stands for digestion rate. Different letters within a column indicate significant differences ($P \leq 0.05$).

Treatments	Smell	WC (%)	pH value	Nutrient components (%)			DR (%)
				Protein	Fat	Fiber	
Non-fermented corn stalks	No particular smell	48 ± 1.3b	7.8 ± 0.3a	6.1 ± 0.7c	1.6 ± 0.2c	36.5 ± 2.8b	65 ± 4.7c
"Huge-fermenter" forage	Thin acid and spicy	66 ± 1.5a	6.7 ± 0.2b	6.9 ± 0.6b	1.8 ± 0.3b	33.6 ± 2.9c	78 ± 3.6b
"Bread" forage	Thin acid and spicy	69 ± 1.7a	6.3 ± 0.1c	7.4 ± 0.3a	2.1 ± 0.3a	32.3 ± 2.7c	89 ± 5.8a

Cattle digestion rates (DR) were calculated by analyzing the nutrients of forage (N_1) and cattle dung (N_2) using the formula:

$$DR(\%) = (N_1 - N_2)/N_1.$$

Three replicates were used in this experiment.

2.6. Statistical analysis

Correlations were analyzed between household income and the proportion of corn stalks used as forage. Information on household income and corn grain yields for each household was obtained by use of questionnaires. Corn residues were recalculated based on corn grain yields according to the method described by Zeng et al. [33]. The curved fit in Sigma Plot (Ver. 10.0, SPSS, Chicago, IL, USA) was applied in analyzing those correlations. Data were analyzed using a one-way analysis of variance (ANOVA) in SPSS (Ver. 11, SPSS, Chicago, IL, USA). Differences between differently-treated corn stalks were considered significant at $P \leq 0.05$.

3. Results and discussion

3.1. Anaerobic fermentation of corn stalks

The physical and biochemical characteristics of both "bread" forage and "huge-fermenter" forage were much better than those in the non-fermented corn stalks in cattle feed. As shown in Table 1, the 30-d fermented corn stalks had a particular smell (thin acid and spicy), which was more favorable for cattle [8,34]. Water contents (WC) of the 30-d fermented "bread" forage and "huge-fermenter" forage were around 68%, but WC was only about 48% for 30-d non-fermented corn stalks. Crude protein and crude fat contents were much higher but crude fiber was much lower in both fermented forages than in the control. There were no significant differences between "bread" and "huge-fermenter" forages in crude protein and crude fat contents. Nevertheless, significant reductions in fiber content were noted in both fermented forages than in the control. pH values were significantly lower but the cattle digestion rates were considerably higher in both fermented forages than in the control. pH values of fermented forages (<7) were considerably lower than that of the control (>7). This agrees with results of Wang [24], who reported that acidic corn stalk was easier for animal digestion.

These results indicate that anaerobic fermentation of crop residues might be one of the foremost methods of ensuring the circulation of agricultural elements. Although the "bread" forage was more adoptable than the "huge-fermenter" forage for feeding cattle, the cost for producing "bread" forage was almost twice that of "huge-fermenter" forage. As a result, farmers preferred the latter fermentation method.

3.2. Cattle growth

Anaerobic fermentation may significantly enhance the nutrients contents of crop residues (including corn stalks) and decrease fiber content and pH values, leading to increase in cattle digestion rates [35,36]. In addition, increased palatability and the unique smell of fermented forages might stimulate a cattle's appetite, leading to a result of increased consumptions of fermented forages. Therefore, cattle weight increased significantly when cattle were fed fermented forages over non-fermented corn stalks (Fig. 8A).

Corn stalk consumption per cattle was significantly higher in both the "bread" forage and the "huge-fermenter" forage

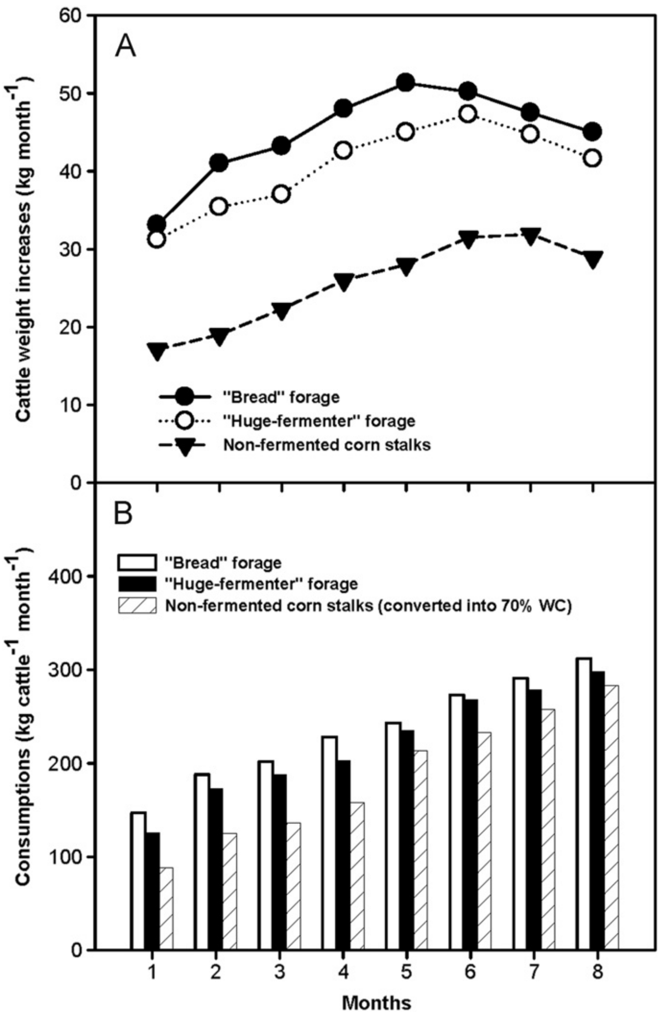

Fig. 8. Cattle weight increases (A) and consumptions of differently-fermented forage per capita (B) in each month after treatments. WC stands for water content.

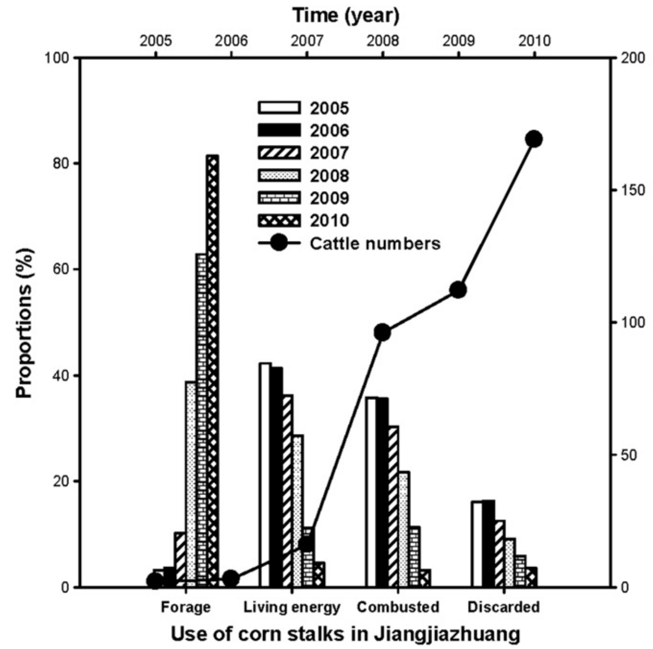

Fig. 9. Cattle numbers and use of corn stalks in Jiangjiazhuang from 2005 to 2010.

Fig. 10. After the experiment, neat and orderly streets without crop residues. (Photo source: Sun Shanshan).

treatments than in the control (Fig. 8 B). In addition, consumption of the "bread" forage was significantly higher than that of the "huge-fermenter" forage months during 1–4, but no significant differences were noted during months 5–8. This might indicate that young cattle had higher forage quality requirements than adult cattle [37,38]. Relatedly, variation in trends regarding increasing cattle weight was similar to trends in corn stalk consumption.

Since anaerobic fermentation technology improved, increasingly more corn stalks were used as cattle forage in Jiangjiazhuang (Fig. 9). The costs of feeding cattle then decreased dramatically allowing the farmers to increase profit margins. As a result, livestock industry developed rapidly, increasing cattle numbers from 2 in 2005 to 169 in 2010. Eventually, environmental conditions in this village improved significantly, with streets becoming neat and orderly (Fig. 10).

3.3. *Biogas production*

The temperatures of biogas digesters increased an average 7.5 °C by replacing crop residues with cattle dung as a digester substrate and installing heat preservation facilities. The pH of the slurry in the biogas digesters also decreased to 5.6, and as a consequence, the rate of biogas production rate increased significantly (99.3%) (Table 2). Pohekara et al. [39] reported that cattle dung is a good substrate at generating biogas, as it comes from the cattle's digestion system, which contains anaerobic bacteria helpful in producing biogas [40,41]. Proper pH levels and temperatures for methanogens are especially important in the initial stages of fermentation [42–44]. In addition, higher temperatures in digesters may reduce the period needed to achieve optimum fermentation for biogas production [45–47]. Therefore, in this study, biogas digesters, biogas yield and the proportion of biogas energy used in household fuel increased drastically after the project began (Fig. 3).

3.4. *Nutrients of differently-fermented cattle dung*

Crop productivities have significantly decreased in recent years due to declining of soil quality as the use of chemical fertilizers has increased while use of organic fertilizers has decreased [48]. In this study, cattle dung output rapidly increased

Table 2
Responses of digester temperature, pH and biogas production rate to digester substrate and temperature in family-sized (7 m^3) biogas digesters. Data are means ± SE ($n=3$). FM stands for fresh mass. Different letters within a column indicate significant differences ($P \leq 0.05$).

Treatments	Digester temperature (°C)	pH	Biogas production rate (ml kg^{-1} FM)
Crop residues used as digester substrate	21.2 ± 3.1b	6.7 ± 1.0a	315 ± 11c
Cattle dung used as digester substrate	25.1 ± 2.7b	5.9 ± 1.2b	562 ± 17b
Cattle dung as substrate + heat preservation measures	28.7 ± 3.6a	5.6 ± 1.1c	628 ± 23a

Table 3
Water content, pH and nutrient components of differently-fermented cattle dung. Data are means ± SE ($n=3$). Different letters within a column indicate significant differences ($P \leq 0.05$).

Cattle dung treatments	Water content (%)	pH	Nutrient components (mg g^{-1})			
			Organic C	Available N	Available P	Available K
Fresh cattle dung	77.2 ± 3.1a	8.1 ± 0.6a	6.1 ± 0.2b	0.42 ± 0.1b	0.26 ± 0.03b	0.13 ± 0.02b
6-month composted cattle dung	52.7 ± 2.7b	6.8 ± 0.3b	6.9 ± 0.4a	0.51 ± 0.2a	0.32 ± 0.05a	0.16 ± 0.02a
6-month fermented in biogas digesters	81.4 ± 3.6a	5.9 ± 0.4c	6.8 ± 0.3a	0.53 ± 0.2a	0.35 ± 0.06a	0.17 ± 0.03a

in the village, resulting in production of abundant organic fertilizers (differently-fermented cattle dung), which can be applied to enrich croplands. As shown in Table 3, the organic C and available N, P and K contents were significantly higher in fermented cattle dung (both composted and biogas digester substrates) than in fresh cattle dung. This could be from anaerobic bacteria transforming some void N, P and K into available forms during the process of fermentation. The water content of 6-month composted cattle dung was much lower than that in both fresh cattle dung (31.7%) and 6-month digester substrates (35.2%), while there were no significant differences between fresh cattle dung and 6-month digester substrates. The fresh cattle dung was alkaline (pH = 8.1), while the fermented cattle dung was acidic (pH = 6.8 for 6-month composted cattle dung and pH = 5.9 for 6-month digester substrates). Acidic conditions are beneficial for fermentative bacteria, and as a consequence, the nutrient components can be enhanced through a period of fermentation [35]. Fermented organic fertilizer application in croplands might more effectively enhance the soil organic carbon content and crop productivities than fresh cattle dung [49]. It is important to note that the amount of chemical fertilizers applied could be drastically reduced in fertile croplands by applying more organic fertilizers, resulting in a considerable reduction in the consumption of chemical fertilizer. Effective soil carbon sequestration and the significant reduction in chemical fertilizer production might contribute to reduce greenhouse gas emission and alleviate global warming [26,50].

Because pre-composted cattle dung can be more easily degraded in an anaerobic system than in an aerobic system due to depolymerization of complex organic fractions in aerobic conditions [51], production of pre-composted cattle dung should be emphasized to generate biogas in the future.

3.5. Correlations between farmers' income and corn stalk forage rate

Proper utilization of corn stalks and livestock feeding in rural areas enhanced farmers' income. As shown in Fig. 11A, the proportion of corn stalks used as forage increased from 1.1% in 2005 to 78.9% in 2010 in this village. As a result, the farmers' income increased by 11.6% in 2010 over 2005. Before the experiment, most parts of the corn stalks were discarded or combusted directly in the field, with only a small fraction used as household fuel. Also, only a small amount of crop stalks was used as forage due to a lack of fermentation technology and financial/medical support [4,5]. Because of a demonstration of our study, the

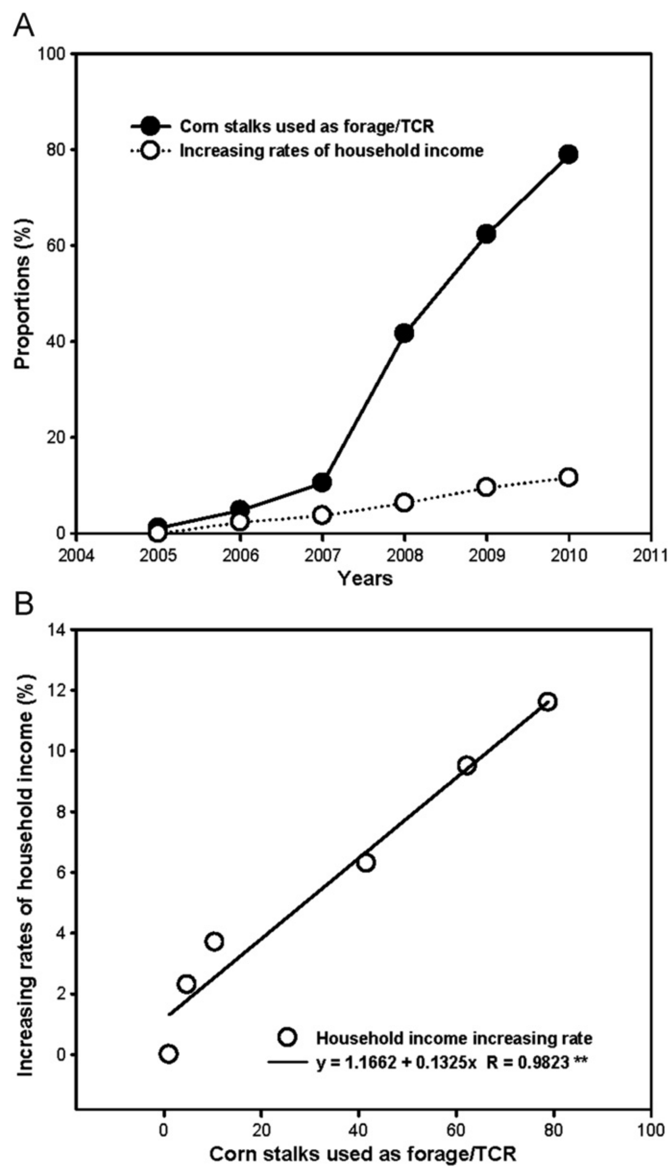

Fig. 11. The proportion of corn stalks used as forage in total corn stalks (TCR) and increasing rates of household income from 2005 to 2010 (A); correlations of increasing rates of household income and the proportion of corn stalks used as forage/TCR (B).

livestock industry developed rapidly in the study area; the proportion of corn stalks used for forage and biogas used for household fuel increased remarkably in recent years. A significant positive correlation ($r=0.9832^{**}$) was noted between the increasing rate of farmers' income and livestock development relative to the feed conversion ratio of corn stalks (Fig. 11B). Thus, we conclude that farmers profited considerably by feeding cattle and saving energy and chemical fertilizer costs.

4. Conclusions

4.1. Anaerobic fermentation elevated corn stalk use efficiency

Anaerobic fermentation effectively enhanced nutrient content of corn stalks and cattle digestion rates. Advanced fermentation technology of corn stalks benefited livestock feeding and enhanced corn stalk use efficiency. Suitable utilization of corn stalks could reduce biomass waste and alleviate air pollution caused by combustion in the field in rural areas worldwide, especially in developing countries.

4.2. Proper fermentation conditions enhanced biogas output

Biogas output was positively correlated with the composition of digester substrate and proper fermentation conditions, such as pH levels and temperature. Cattle dung used as the main digester substrate and heat preservation measures effectively enhanced biogas productivity under these experimental conditions.

4.3. Fermented cattle dung might increase soil carbon sequestration

Application of differently-fermented cattle dung in soils enhanced organic C content more effectively than did application of non-fermented cattle dung. Use of a large amount of organic fertilizer reduced the consumption of chemical fertilizers. Soil carbon sequestration and a reduction in the production of chemical fertilizers would contribute to alleviating regional or global warming.

Acknowledgments

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